# Energy-saving UAV-Assisted Multiuser Communications with Massive MIMO Hybrid Beamforming

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***Abstract*—In this paper, we consider hybrid beamforming for unmanned aerial vehicle (UAV)-assisted communications with massive multiple-input multiple-output (MIMO). Using a hybrid beamforming design, we derive an approximate closed-form expression of rate and provide a power allocation design under the line-of-sight (LoS) channels. It is revealed that the total transmit power should be inversely proportional to the number of antennas of UAV in order to satisfy the rate requirement of each user. Furthermore, we propose the optimal location design of the UAV. For the special case the pathloss exponent is $2$, the optimal location is the weighted average location of all users where the weights are signal to interference plus noise ratio (SINR) requirements of all users. It is shown that the weighted average location could be an approximate method to design the UAV location with little performance gap to the optimal location even when path loss exponent is not $2$.**

***Index Terms*—Hybrid beamforming, massive MIMO, unmanned aerial vehicle.**

## I. Introduction

In existing cellular networks, ground base stations with fixed locations are deployed to provide seamless coverage and reliable connections for mobile terminals. Due to blockage in environment, the channel quality can vary dramatically across various environments. To complement existing ground base stations, the emerging unmanned aerial vehicle (UAV)-assisted wireless communications can provide economical wireless access to areas without satisfactory infrastructure coverage [1], [2]. The mobility of UAVs allows them to dynamically serve users over a wide area. Moreover, line-of-sight (LoS) comunication links can be established in most scenarios with the aid of UAVs which potentially leads to better communication channels. There are different types of UAVs with varying sizes and capabilities that are used in multitude applications [3]. Depending on the power source, their connectivity range varies from a few meters up to several kilometers, and their flight time varies from a few minutes up to tens of hours [2].

Recently, exploiting research on UAV communication in three-dimensional space attracts increasing attention to fully exploit the benefits of the UAV mobility. By treating mobile UAVs as flying base stations (BSs), existing studies proposed efficient deployments of UAVs for enlarging wireless coverage [4], [5]. Power allocation is crucial for UAVs, because the UAV's size and weight constraints limit the on-board energy storage. To address this issue, [6] designed UAV trajectory to maximize energy efficiency. In [7], the authors considered to maximize the coverage by using the minimal transmit power. [8] jointly optimized the transmit power and trajectory to maximize the minimum average throughput within a given time length. [9] considers the downlink of a system servicing a set of mobile users via several UAVs acting as distributed antennas and provided the location design for two special cases where pathloss exponent is 2 or UAVs at very high altitudes. Note that all aforementioned studies focused on UAVs equipped with a single antenna. For UAVs equipped with multiple antennas, [10] studied the achievable rate of an uplink cognitive radio system using a UAV relay. In addition, a 3-D elliptic-cylinder UAV channel model was proposed in [11]. It is important to study UAVs equipped with multiple-input multiple-output (MIMO), as it requires less power than single antenna UAV under a given quality-of-service (QoS). Although there have been researches on UAV with MIMO, it is challenging to further consider massive MIMO for the UAV due to weight and size constraints [1], [2]. The hybrid beamforming is suitable for the UAV since it saves both power consumption and computation complexity. However, to the best of our knowledge, few contributions have been devoted to the problem of power minimization for UAVs equipped with antenna arrays, especially with large-scale antenna arrays.

In this work, we study the UAV networks with UAV BS using multiuser massive MIMO hybrid precoding. In this work, dedicated UAVs are employed as aerial BSs, to assist the wireless communications of ground nodes, which we refer to a number of applications detailed as UAV-assisted wireless

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communication in [1], [2]. Moreover, the UAV BS also plays an important role in many special scenarios without working ground BSs, for example, disasters or scientific expedition in the field [12]. It is notable that although the topic of hybrid beamforming has been well investigated in conventional cellular networks, the involvement of hybrid beamforming in UAV systems makes the problem more complicated and are even harder to solve, i.e, UAV coordinate optimization. In detail, the hybrid beamforming is based on physical channels which are related to the UAV location. To minimize the total transmit power, we propose the optimal UAV location design based on the popular hybrid precoding method under LoS channels. For the special case $\alpha = 2$, the optimal solution of UAV location reduces to the expression of a weighted average of user locations. We also show that, the weighted average location of all users could be a good approximation of the optimal choice of UAV location.

## II. System Model

We consider a downlink massive MIMO UAV-aided wireless communication system with one UAV equipped with $M$ antennas serving $K$ single-antenna ground users. The UAV is deployed as a flying BS located at ($x_0$, $y_0$, $H$), where $H$ is a constant altitude for safety considerations, while the location of ground user $k$ is denoted by ($x_k$, $y_k$, $z_k$). For a certain altitude, we expect that the channels between the UAV and users are dominated by the LoS type. It is notable that we suppose that the UAV works at high frequency bands, e.g., mmWave , due to the advantage of having LoS path with high probablity and the facility of developing a relatively large antenna array for strong beams [1]. To fully describe the characteristics of the wireless channel, we express the channel between the UAV and user $k$ as [6], [8]

$$\mathbf{h}_k = \sqrt{M\beta_k}\mathbf{a}(\theta_k) \tag{1}$$

where $\beta_k$ reflects the large scale shadowing, $\mathbf{a}(\theta_k)$ denotes the fast fading factor vector which models the propagation condition of the channel and $\theta_k$ is the azimuth angle of departure (AOD) of user $k$. Specifically, the large scale shadowing can be expressed as $\beta_k = \beta_0 d_k^{-\alpha} \overset{(a)}{=} \beta_0 \left(\sqrt{(x_0-x_k)^2+(y_0-y_k)^2+(H-z_k)^2}\right)^{-\alpha}$ where $\alpha$ is the pathloss exponent, $\beta_0$ denotes the channel power gain between the UAV and users at the unit distance, and $d_k$ is the distance between the UAV and user $k$ and (a) uses $d_k = \sqrt{(x_0-x_k)^2+(y_0-y_k)^2+(H-z_k)^2}$ which contains the effect of the UAV location. Considering the common uniform linear array (ULA), the LoS channel can be represented by $\mathbf{a}(\theta_k) = \frac{1}{\sqrt{M}}\left[1, e^{j2\pi\frac{d}{\lambda}\cos\theta_k}, ..., e^{j2\pi\frac{(M-1)d}{\lambda}\cos\theta_k}\right]^T$ where $\lambda$ denotes the signal wavelength, and $d$ represents the distance between adjacent antenna elements.

Due to hardware constraints, the UAV employs hybrid beamforming where the number of RF chains is far less than the number of antennas, i.e., $N_{RF} < M$. Note that we assume a fully-connected structure where each RF chain is connected to every antenna through a phase shifter. To enable multistream communications, $N_{RF}$ is assumed to be no less than $K$, i.e., $N_{RF} \geq K$. Since RF chains are responsible for a large amount of power, it is more practical to set $N_{RF} = K$ for the UAV BS which can not afford too much power. Note that $N_{RF} \geq K$ or $N_{RF} = K$ is the general assumption of the hybrid precoding [13]–[16]. For $N_{RF} \geq K$, we can simply use the strategy for turning off the additional RF chains for the sake of power saving as in, e.g., [14].

Assuming a block-fading channel model, the received signal at all users is

$$\mathbf{y} = \mathbf{H}^H\mathbf{FWPs} + \mathbf{n}, \tag{2}$$

where $\mathbf{P} = \text{diag}[\sqrt{p_1}, ..., \sqrt{p_K}]$ refers to the power allocation matrix, $\mathbf{F} = [\mathbf{f}_1, ..., \mathbf{f}_{N_{RF}}] \in \mathbb{C}^{M\times N_{RF}}$ and $\mathbf{W} = [\mathbf{w}_1, ..., \mathbf{w}_K] \in \mathbb{C}^{N_{RF}\times K}$ are respectively the analog and digital beamforming matrices, $\mathbf{H} = [\mathbf{h}_1, ..., \mathbf{h}_K] \in \mathbb{C}^{M\times K}$ stands for the channel matrix, $\mathbf{s} = [x_1, ..., x_K]^T \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ represents the data vector, and $\mathbf{n} = [n_1, ..., n_K]^T \sim \mathcal{CN}(\mathbf{0}, \sigma_n^2\mathbf{I})$ is the noise vector. Since the phase shifters can only change the angles of signals, the $i$-th element of $\mathbf{f}_k$ is normalized as $|f_{ki}| = \frac{1}{\sqrt{M}}$. From (2), the received signal of user $k$ becomes $y_k = \sqrt{p_k}\mathbf{h}_k^H\mathbf{F}\mathbf{w}_k s_k + \sum_{j\neq k}\sqrt{p_j}\mathbf{h}_k^H\mathbf{F}\mathbf{w}_j s_j + n_k$, where $y_k$, $s_k$ and $n_k$ denote the $k$-th element of $\mathbf{y}$, $\mathbf{s}$ and $\mathbf{n}$, respectively.

Generally, the hybrid beamforming design is non-trival due to the constant amplitude constraints of phase shifters. Here, we would like to employ a popular idea to design hybrid beamforming which seperates the design into two stages [13]–[16]: (1) The analog beamforming reaps diversity by maximizing the signal power for each user while ignoring the interference among users; (2) The digital beamforming is designed by a linear precoder to manage the resulting multiuser interference. In detail, the UAV first maximizes the signal power by

$$\mathbf{f}_k = \text{argmax}\,|\mathbf{h}_k^H\mathbf{f}_k|^2. \tag{3}$$

Then, the digital precoding is designed according to the equivalent channel vector between the UAV and each user, which is given as

$$\mathbf{g} = \mathbf{F}^H\mathbf{h}. \tag{4}$$

With the equivalent channels, we can write the zero-forcing digital precoding as

$$\mathbf{V} = \mathbf{G}(\mathbf{G}^H\mathbf{G})^{-1}, \tag{5}$$

where $\mathbf{G} = [\mathbf{g}_1, ..., \mathbf{g}_K]$. Then, we normalize the digital precoding to guarantee transmit power constraints. It yields $\mathbf{w}_k = \frac{\mathbf{v}_k}{\|\mathbf{F}\mathbf{v}_k\|_F}$, where $\mathbf{v}_k$ is the $k$-th column of $\mathbf{V}$.

## III. Problem Formulation and Solution

The ground BS has a fixed location. One can only design beamforming and resource allocation for performance enhancement. Once the users change their locations, the BS can not move. However, the mobile BS, UAV, could dynamically adjust its location in real-time to improve user performance. Moreover, the ground BS is powered by cables which does not have serious power concerns. The studies on ground BS usually design beamforming and resource allocation to maximize the system spectral efficiency, while the stored energy for the UAV is limited. Therefore, instead of maximizing the system rate, it makes more sense for the UAV BS to minimize the transmit power while statisfying the QoS of users in terms of spectral efficiency. Note that the location of UAV affects the channel, which further has impacts on the rate. Thus, our optimization problem is written as

$$\min_{\{p_k\}_{k=1}^{K},x_0,y_0} \quad P_{\text{total}} \tag{6}$$

$$s.t. \quad R_k \geq \tau_k, \forall k \tag{7}$$

$$x_{\min} \leq x_0 \leq x_{\max},\ y_{\min} \leq y_0 \leq y_{\max} \tag{8}$$

where $P_{\text{total}} = \sum_{k=1}^{K} p_k$ refers to the total transmit power, $[x_{\min}, x_{\max}]$ and $[y_{\min}, y_{\max}]$ respectively represent the ranges of x-axis and y-axis of the UAV location, $\tau_k$ denotes the minimal rate requirement of user $k$ and the rate of user $k$ is

$$R_k = B \log_2 \left( 1 + \frac{p_k |\mathbf{h}_k^H \mathbf{F} \mathbf{w}_k|^2}{\sum_{j \neq k} p_j |\mathbf{h}_k^H \mathbf{F} \mathbf{w}_j|^2 + \sigma_n^2} \right), \tag{9}$$

where $B$ is the system bandwidth.

To further simplify the problem, we would like to transfer (6) to a problem with fewer optimization variables and constraints. Since the power allocation has impact on the rate constraint in (7) and the UAV location affects (7) and ranges of x-axis and y-axis, we first focus on simplifying (6) by deriving a simple expression to characterize the relationship between the rate and $\{p_k\}_{k=1}^{K}$ in the following proposition.

*Proposition 1:* For the LoS case in massive MIMO with hybrid precoding, the rate for user $k$ is well approximated by

$$R_k = B \log_2 \left( 1 + \frac{M p_k \beta_k}{\sigma_n^2} \right). \tag{10}$$

Proof: See Appendix A.

By substituting (10) into (7), we have the minimum transmit power of user $k$ as: $p_k = \frac{(2^{\tau_k/B}-1)\sigma_n^2}{M\beta_k} = \frac{(2^{\tau_k/B}-1)\sigma_n^2}{M\beta_0} d_k^{\alpha}$.It is not difficult to obtain the following observation.

*Remark 1:* To satisfy the rate requirement of each user, the minimum total transmit power of UAV is derived as

$$P_{\text{total}} = \frac{\sigma_n^2}{M\beta_0} \sum_{k=1}^{K} (2^{\tau_k/B} - 1) d_k^{\alpha}. \tag{11}$$

*Remark 2:* From Remark 1, the minimum required total transmit power, i.e., $P_{\text{total}}$, increases linearly with $\frac{1}{M}$.

Although Remark 2 is obtained in massive MIMO, simulation results in Section IV show that the conclusions still hold when the number of antennas at the UAV is not quite large.

With the beamforming design, we then need to optimize the location of UAV, i.e., $(x_0, y_0)$. The problem becomes

$$\min_{x_0,y_0} \quad \sum_{k=1}^{K} \rho_k d_k^{\alpha} \quad s.t. \quad (8) \tag{12}$$

where $\rho_k \triangleq (2^{\tau_k/B}-1)$ is the signal-to-interference-plus-noise ratio (SINR) requirement of user $k$. Note that $\rho_k$ is the quality-of-service (QoS) requirement in terms of SINR requested by user $k$. In other words, it indicates that the achieved SINR of user $k$ should be at least no smaller than the value of $\rho_k$ in order to make user $k$ satisfied.

Applying the Karush-Kuhn-Tucker (KKT) conditions, we write the Lagrangian as: $L = \sum_{k=1}^{K} \rho_k d_k^{\alpha} + \gamma_1(x_{\min} - x_0) + \gamma_2(x_0 - x_{\max}) + \gamma_3(y_{\min} - y_0) + \gamma_4(y_0 - y_{\max})$. Then, the KKT conditions should be

$$\frac{\partial L}{\partial x_0} = 0,\ \frac{\partial L}{\partial y_0} = 0, \tag{13}$$

(8)

$$\gamma_i \geq 0,\ \gamma_1(x_{\min} - x_0) = \gamma_2(x_0 - x_{\max}) = \gamma_3(y_{\min} - y_0) = \gamma_4(y_0 - y_{\max}) = 0. \tag{14}$$

Generally, the location of UAV satisfies that $x_{\min} < x_0 < x_{\max}$ and $y_{\min} < y_0 < y_{\max}$, which indicates that $\gamma_i = 0$. Then, we focus on $\frac{\partial L}{\partial x_0}$, which is expressed by

$$\frac{\partial L}{\partial x_0} = \frac{\partial \sum_{k=1}^{K} \rho_k d_k^{\alpha}}{\partial x_0} \overset{(a)}{=} \alpha \sum_{k=1}^{K} \rho_k (d_k^2)^{\frac{\alpha}{2}-1} (x_0 - x_k), \tag{15}$$

where (a) is by substituting $d_k = \sqrt{(x_0 - x_k)^2 + (y_0 - y_k)^2 + (H - z_k)^2}$. Similarly, we can get $\frac{\partial L}{\partial y_0} = \alpha \sum_{k=1}^{K} \rho_k (d_k^2)^{(\frac{\alpha}{2}-1)} (y_0 - y_k)$.

By letting $\frac{\partial L}{\partial x_0} = \frac{\partial L}{\partial y_0} = 0$ and recalling that $\alpha > 0$, we get the necessary conditions:

$$\sum_{k=1}^{K} \omega_k (x_0 - x_k) = \sum_{k=1}^{K} \omega_k (y_0 - y_k) = 0. \tag{16}$$

If we define the optimal UAV location as $(x_0^*(\alpha), y_0^*(\alpha))$, it is the solution of (16). It is difficult to obtain a closed-form solution to (16) due to non-integer exponents $\alpha$. However, (16) can be efficiently solved using existing software tools.

Moreover, we also get a closed-form solution to a special case to (16) in the following observation.

*Lemma 1:* If $\alpha = 2$, the optimal location of the UAV can be represented by

$$(x_0^*(2), y_0^*(2)) = \left( \frac{\sum_{k=1}^{K} \rho_k x_k}{\sum_{k=1}^{K} \rho_k}, \frac{\sum_{k=1}^{K} \rho_k y_k}{\sum_{k=1}^{K} \rho_k} \right), \tag{17}$$

which is the weighted average location of users.

*Remark 3:* When the pathloss exponent is 2, according to Lemma 1, the optimal UAV location is the weighted average location of all users, where weights are the SINR requirements.

Even though Lemma 1 and Remark 3 are obtained for $\alpha = 2$, numerical resutls in Section IV demonstrate that the weighted locations in (17) also obtain great performance even when $\alpha$ is not 2.

## IV. Simulation Results

In this section, we provide simulation results to verify the results in this paper. We consider one UAV BS and several ground users. The location and

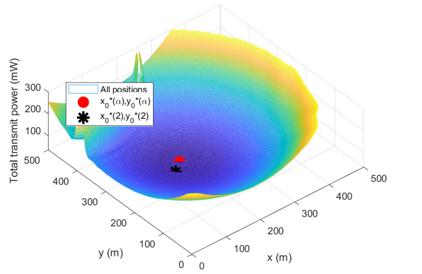


Fig. 1: Power consumption with $M = 64$ at all locations (44.2917 mW at $(x_0^*(\alpha), y_0^*(\alpha)) = (192.0200, 273.3940)$, 47.4213 mW at $(x_0^*(2), y_0^*(2)) = (160.2886, 249.0210)$).

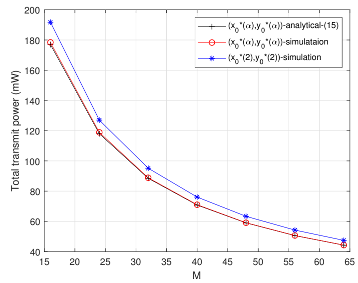


Fig. 2: Power consumption versus $M$.

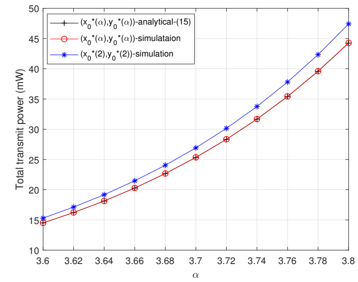


Fig. 3: Power consumption versus $\alpha$ with $M = 64$.

TABLE I: Simulation Parameters

| Parameters | Notation | Typical Values |
|---|---|---|
| Number of users | $K$ | 4 (except Fig. 5) |
| Communication bandwidth | $B$ | 1MHz |
| The noise power density | $\sigma_n^2/B$ | -169dBm/Hz |
| The channel power gain at 1m | $\beta_0$ | $1.42 \times 10^{-4}$ |
| The pathloss exponent | $\alpha$ | 3.8 (except Fig. 3) |
| UAV flying height | $H$ | 200m |
| UAV x-axis range | $[x_{\min}, x_{\max}]$ | [0,500](m) |
| UAV y-axis range | $[y_{\min}, y_{\max}]$ | [0,500](m) |
| UAV z-axis range | $[z_{\min}, z_{\max}]$ | [1,25](m) |

rate requirement for each user is generated according to uniformly random distribution. Specifically, the locations of all users are $(460.1660, 211.4178, 24.5933)$, $(26.3385, 273.9355, 8.2349)$, $(368.9290, 471.3685, 17.8264)$, $(134.5597, 208.8721, 16.9921)$ (m,m,m) and the rate requirements of all users are $1.2914, 2.4484, 2.0048, 4.2554$ (Mbits/s). Other parameters are shown in TABLE I.

We compare the total transmit power of the UAV BS at all locations in Fig. 1. The minimal power obtained by a exhaustive search (using the step as 1 (m)) is 44.2906 mW. It is observed from Fig. 1 that the total transmit power of UAV at $(x_0^*(\alpha), y_0^*(\alpha))$ is almost the same as that of optimal location where the difference is $\frac{44.2917-44.2906}{44.2906} = 0.0024\%$. Moreover, even if $\alpha$ is far larger than 2 ($\alpha = 3.8$), the power cost at $(x_0^*(2), y_0^*(2))$ is also very close to $(x_0^*(\alpha), y_0^*(\alpha))$ with the difference $\frac{47.4213-44.2917}{44.2917} = 7.0659\%$. Therefore, it is acceptable to conclude $(x_0^*(\alpha), y_0^*(\alpha))$ as the optimal location of the UAV BS and $(x_0^*(2), y_0^*(2))$ is a good approximate location design with little gap to the optimal location.

Fig. 2 demonstrates the total transmit power versus the number of antennas at the UAV. It is not only verified that the performance gap between $(x_0^*(\alpha), y_0^*(\alpha))$ and $(x_0^*(2), y_0^*(2))$ is small, but also shown that the power values obtained from (11) are very close to the exact total power consumption. Note that (11) is still very accurate even if $M$ is not large ($M = 16$). It is due to the fact that the channels are decided by the UAV location which is chosen by the system. If the UAV location is optimized, the UAV intends to locate at a place with high signal power and small interference where physical channel paths are approximately orthogonal. In this case, it is acceptable and appropriate to assume orthogonal channel paths in (18) even if $M$ is not large.

In Fig. 3, we provide the total tranmit power of the UAV BS with the varying channel pathloss exponent. As expected, it is revealed that the transmit power should increase with $\alpha$ to mitigate the growing signal power loss. Moreover, the performance gap between $(x_0^*(\alpha), y_0^*(\alpha))$ and $(x_0^*(2), y_0^*(2))$ also increases with $\alpha$. Nonetheless, for the case $\alpha = 3.8$ (which is far larger than 2), the performance difference between $(x_0^*(2), y_0^*(2))$ and $(x_0^*(3.8), y_0^*(3.8))$ is still quite small.

To show the system performance with large $K$, we also provide simulation results with a large number of users and antennas but fixing the ratio of $K/M$ and $K = N_{RF}$ in Fig. 4. In the figure, the systems with different $\{K\}$'s have the same sum rate and the rate of each user is the same. With the same sum rate, it is shown that the transmit power fall with $K$.

We also compare our proposed method with average location of users and [9] using simulation results in Fig. 5. Note that we use the method to choose the UAV location in [9] and reduce the number of UAVs to one. As shown in Fig. 5, the proposed method outpeforms the other location designs.

Generally, the LoS channel paths dominate the wireless channels in UAV networks. However, the UAV could also be applied over multipath channels, which also includes NLoS (Non-Line-of-Sight) channel paths. In this case, if the UAV only knows the information of the LoS channel path, the rate of each user can not meet the constraints ($R_k < \tau_k$). To investigate the performance deterioration, we also provide simulation results over Rician channels. The channel vector between the UAV and user $k$ is $\mathbf{h}_k = \sqrt{\frac{\kappa_k}{1+\kappa_k}}\mathbf{h}_k^{LoS} + \sqrt{\frac{1}{1+\kappa_k}}\mathbf{h}_k^{NLoS}$, where $\mathbf{h}_k^{LoS}$ is calculated according to (1), $\mathbf{h}_k^{NLoS}$ is randomly distributed as $\mathbf{h}_k^{NLoS} \sim \mathcal{CN}\left(\mathbf{0}, \frac{\|\mathbf{h}_k^{LoS}\|_F^2}{M}\mathbf{I}\right)$ and $\kappa_k$ is the Rician $K$-factor of the $k$-th user channel in which $\kappa_1 = \ldots = \kappa_K = \kappa$ is assumed. We denote $R(\alpha)$ and $R(2)$ as the sum rate for the UAV at $(x_0^*(\alpha), y_0^*(\alpha))$ and $(x_0^*(2), y_0^*(2))$, respectively. $\tau$ stands for the sum rate requirements ($\tau = \sum_{k=1}^{K} \tau_k$).

Fig. 6 illustrates the performance deterioration of the proposed designs over Rician channels with varying $\kappa$. According

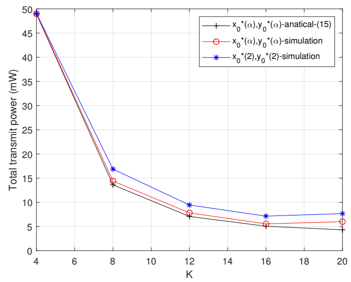


Fig. 4: Power consumption versus $K$ with $M/K = 16$.

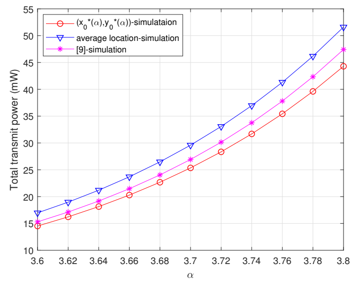


Fig. 5: Power consumption versus $\alpha$ with $M = 64$.

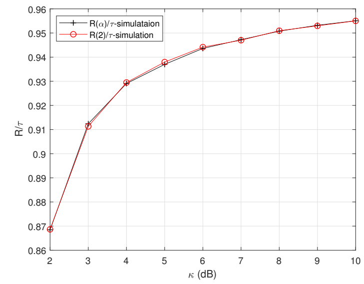


Fig. 6: Sum rate related to sum rate requirements versus $\kappa$ with $M = 64$.

to Fig. 6, $\frac{R(\alpha)}{\tau}$ and $\frac{R(2)}{\tau}$ increase with $\kappa$ and exceed 0.95. Even when NLoS components are not small and can not be ignored ($\kappa = 3$ dB), the UAV BS could still fulfill around 90% rate requirements. Moreover, $R(\alpha)$ and $R(2)$ are almost the same which indicates that the performance of $(x_0^*(2), y_0^*(2))$ approaches that of $(x_0^*(\alpha), y_0^*(\alpha))$ over Rician channels.

## V. Conclusions

UAV-assisted communications with multiuser massive MIMO hybrid beamforming were studied to provide coverage for ground users in this work. With a hybrid beamforming method, power allocation and location designs were proposed to minimize the power while satisfying the rate requirements of all users. For the special case with path loss exponent equals to 2, the optimal location could be expressed as the weighted average location of all users.

## Appendix A
## Proof of Proposition 1

For massive MIMO, the channel model can be well approximated by virtual channel representation [17]

$$\mathbf{h}_k = \sqrt{M\beta_k}\mathbf{t}_k, \tag{18}$$

where $\mathbf{t}_k = \mathbf{a}(\hat{\theta}_k)$ in which $\hat{\theta}_k = \underset{\hat{\theta}_k \in \{\frac{2\pi}{M}, \frac{4\pi}{M}, ..., \frac{2\pi(M-1)}{M}\}}{\operatorname{argmin}} |\hat{\theta}_k - \theta_k|$. According to (3), the analog precoding for user $k$ should be $\mathbf{f}_k = \mathbf{t}_k$ which further yields $\mathbf{F} = [\mathbf{t}_1, ..., \mathbf{t}_K]$. From the definition of effective channels in (4), we have

$$\begin{aligned}\mathbf{G}^H =& \mathbf{H}^H\mathbf{F} = [\sqrt{M\beta_1}\mathbf{t}_1, \ldots, \sqrt{M\beta_K}\mathbf{t}_K]^H[\mathbf{t}_1, \ldots, \mathbf{t}_K] \\ =& \begin{bmatrix} \sqrt{M\beta_1}\mathbf{t}_1^H\mathbf{t}_1 & \sqrt{M\beta_1}\mathbf{t}_1^H\mathbf{t}_2 & \cdots & \sqrt{M\beta_1}\mathbf{t}_1^H\mathbf{t}_K \\ \sqrt{M\beta_2}\mathbf{t}_2^H\mathbf{t}_1 & \sqrt{M\beta_2}\mathbf{t}_2^H\mathbf{t}_2 & \cdots & \sqrt{M\beta_2}\mathbf{t}_2^H\mathbf{t}_K \\ \vdots & \vdots & \ddots & \vdots \\ \sqrt{M\beta_K}\mathbf{t}_K^H\mathbf{t}_1 & \sqrt{M\beta_K}\mathbf{t}_K^H\mathbf{t}_2 & \cdots & \sqrt{M\beta_K}\mathbf{t}_K^H\mathbf{t}_K \end{bmatrix}.\end{aligned} \tag{19}$$

Since $\{\mathbf{t}_k\}_{k=1}^K$ are the $K$ orthogonal vectors of a Discrete Fourier Transform (DFT) matrix, it implies that

$$\mathbf{t}_i^H\mathbf{t}_j = \begin{cases} 1, & i = j, \\ 0, & i \neq j. \end{cases} \tag{20}$$

By combining (19) and (20), we obtain $\mathbf{G}^H = \text{diag}[\sqrt{M\beta_1}, \ldots, \sqrt{M\beta_K}]$. Using (5), we calculate $\mathbf{W}$ as $\mathbf{I}$. Substituting above expressions of effective channels and precoding into (9), the rate is approximated by (10). ∎

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